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Light neutralino in the MSSM: An update with the latest LHC results

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Abstract. We discuss the scenario of light neutralino dark matter in the minimal supersymmetric standard model, which is motivated by the results of some of the direct detection experiments — DAMA/LIBRA, CoGeNT, and CRESST. We update our previous analysis with the latest results of the LHC. We show that new LHC constraints disfavour the parameter region that can reproduce the results of DAMA/LIBRA and CoGeNT.

1. Introduction

One of the most dramatic progresses in our understanding of nature in the last decade is the establishment of the dark sector of the universe, which was brought by precision cosmological observations. However, even basic properties — mass and interactions — of Dark Matter (DM) have not been fully understood yet. Numerous experimental efforts to detect DM have been made, and some of the direct detection experiments claim a positive signal that might be originated by DM. The DAMA/LIBRA and CoGeNT collaborations show an annual modulation of signal events, which can be interpreted as the change of the relative velocity of the detectors against the DM halo. In this conference, the long-awaited result of the CRESST collaboration was presented, which indicates a significant excess of events [1]. The results of these experiments suggest a light DM field ($M_\chi \sim 10$ GeV) with a relatively large scattering cross-section with nucleons ($\sigma \sim 10^{-41}$ cm^2); see e.g., [2]. In this talk, we discuss the scenario of light neutralino DM in the minimal supersymmetric standard model (MSSM). Since the lightest supersymmetric particle is protected by R-parity and thus is stable, the lightest neutralino is a good candidate for DM. This possibility has been extensively discussed in the prior studies (cf. [3, 4] and references therein). In our recent paper [5], we inspected the compatibility in the MSSM parameter space between the light neutralino DM scenario and particle physics constraints such as B and K meson decays, neutralino production rate, and Higgs boson searches. Here, we update our analysis with the latest results of the LHC. We will show that the light neutralino DM scenario that is consistent with the results of DAMA/LIBRA and CoGeNT comes into disfavour with the latest LHC bounds, especially constraints from the neutral Higgs boson search.

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2. Light neutralino in the MSSM

What does a light neutralino with mass of around 10 GeV require of the MSSM parameters? The mass of the neutralino is mainly controlled by three parameters, the Bino mass M_1, Wino mass M_2, and higgsino mass μ. Since two of them, M_2 and μ, are related to chargino masses, they must be larger than ~ 100 GeV to satisfy their LEP mass bounds. Therefore, the only possibility is to take $M_1 \sim 10$ GeV to obtain the light neutralino. Consequently, the lightest neutralino in this scenario becomes mostly Bino. The model that we deal with is described by the following nine parameters:

$$\tan\beta, \quad M_1, \quad M_2, \quad M_3, \quad a_0, \quad \mu, \quad m_A, \quad m_{\tilde{q}}, \quad m_{\tilde{\ell}}, \tag{1}$$

where $\tan\beta$ is defined as the ratio of the two Higgs VEV's, M_3 is the gluino mass, a_0 is the universal coefficient for tri-linear scalar couplings, m_A is the CP-odd Higgs mass, and $m_{\tilde{q}}$ and $m_{\tilde{\ell}}$ are the common soft SUSY breaking masses for squarks and sleptons, respectively. We scan them to search for the parameter region in which the light neutralino DM scenario is consistent with the particle physics observations[1].

We assume that the neutralino was thermally produced in the early universe. Since such a light particle is overproduced in the thermal process, an efficient annihilation process is necessary to reproduce the correct relic density. There are two main annihilation processes for light neutralino DM: Sfermion mediation and CP-odd Higgs mediation. It is known that the parameter space in which sfermion mediation becomes the main annihilation process cannot be consistent with the results suggested by DAMA/LIBRA, CoGeNT and CRESST [9] (see also Ref. [10, 11]). Therefore, following Ref. [12], we adopt the Higgs mediation process as the main annihilation process. In order to enhance the Higgs-mediated annihilation, the following three conditions are required of the model parameters: (i) light m_A, (ii) small μ to have a significant amount of higgsino component in the lightest neutralino, and (iii) large $\tan\beta$ to enhance the main annihilation process to a $b\bar{b}$ pair. This parameter choice enhances not only the annihilation process but also many flavour physics processes. In addition, it magnifies the signal of neutral Higgs bosons decaying to lepton pairs at hadron colliders. Therefore, one must carefully inspect the compatibility in the parameter choice between the cosmological requirements and the particle physics constraints.

We employ the following flavour physics processes and categorize them into two groups by their parameter dependence:

- **Group I:** $B \to \tau\nu$, $B \to D\tau\nu$, $D_s \to \tau\nu$, and $K \to \mu\nu$. They essentially depend only on Higgs parameters, $m_{H^\pm}$ and $\tan\beta$.
- **Group II:** $b \to s\gamma$ and $B_s \to \mu^+\mu^-$. These processes depend not only on the Higgs parameters but also on the SUSY parameters such as $m_{\tilde{q}}$ and a_0.

Group I observables complemetarily constrain the parameter space of $m_{H^\pm}$ and $\tan\beta$, which are regardless of the detail of the SUSY parameters [13]. The key observables are $B \to \tau\nu$ and $K \to \mu\nu$. We adopt the following values

$$0.52 < R_{B\tau\nu} < 2.61 \quad \text{and} \quad 0.985 < R_{\ell 23}(K \to \mu\nu) < 1.013, \tag{2}$$

as the allowed range of these observables. $B \to \tau\nu$ excludes intermediate values of $\tan\beta$. On the other hand, $K \to \mu\nu$ disfavours larger values of $\tan\beta$. Therefore, the allowed parameter region with middle-to-high values of $\tan\beta$ is sharply narrowed by combination of these two constraints. After a numerical scan of the parameters Eq. (1), we found that the allowed parameter regions form two separated clusters: (i) A narrow strip at high $\tan\beta$ ($32 \lesssim \tan\beta \lesssim 38$) and (ii) A low

[1] We use the public codes SuSpect [6], micrOMEGAs [7], and SuperIso [8] in our numerical studies.

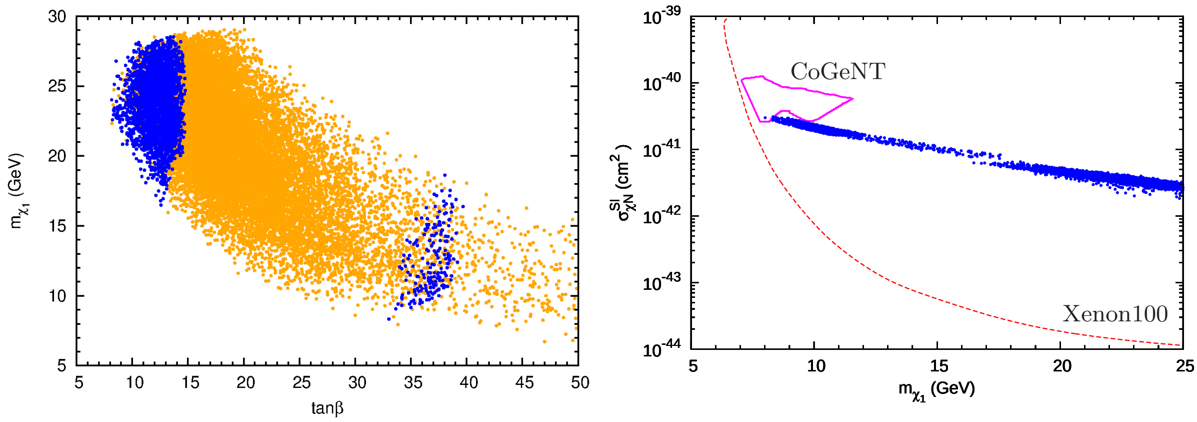

Figure 1. Left: Allowed parameter region on the plane of the lightest neutralino mass and $\tan\beta$. After taking into account all the constraints, two separated regions are left (blue points): (i) A high $\tan\beta$ strip and (ii) A low $\tan\beta$ region. To obtain a light neutralino with $M_{\tilde{\chi}_1^0} < 15$ GeV, a large value of $\tan\beta$ is necessary. Right: Neutralino-nucleon scattering cross-section as a function of mass of the lightest neutralino. The prediction of the high $\tan\beta$ strip roughly coincides with the results of DAMA/LIBRA and CoGeNT. The best-fit region of CRESST is located around $(M_{\tilde{\chi}_1^0}, \sigma_{\rm SI}) \simeq$(20 GeV, 10^{-42} cm^2) [1].

$\tan\beta$ region ($7 \lesssim \tan\beta \lesssim 15$). The mass of the lightest neutralino is inversely proportional to $\tan\beta$, because a lighter neutralino requires a more efficient annihilation process that is enhanced by a large value of $\tan\beta$. As shown in the left plot of Fig. 1, a neutralino with mass lighter than 15 GeV is viable only on the high $\tan\beta$ strip.

Next, we discuss the neutralino-nucleon scattering cross-section. DAMA/LIBRA and CoGeNT suggest relatively large values for the cross-section. In both parameter regions (i) and (ii), the neutralino-nucleon scattering process is mediated by Higgs bosons, and its parameter dependence is similar to that of the neutralino annihilation process. Consequently, the direct detection cross-section becomes large at the light neutralino region on which a large annihilation cross-section is required. As shown in the right plot in Fig. 1, the parameter choice of the high $\tan\beta$ strip approximately reproduces the results of DAMA/LIBRA and CoGeNT.

Since the high $\tan\beta$ strip is standing on the edge of the experimental constraints with delicate tune of the model parameters Eq. (1), it might be easily excluded by an improvement of some of the constraints. Here, we update our previous analysis [5] with the latest LHC results. The bound to the branching ratio of $B_s \to \mu^+\mu^-$ is improved by LHCb with an integrated luminosity of 0.3 fb^{-1} [14], which is constrained to be smaller than 1.5×10^{-8} at 95 % CL. As shown in the left plot in Fig. 2, this new bound excludes all the points in the high $\tan\beta$ region, which satisfy the Higgs mass bounds at LEP. Another crucial constraint is brought from the search for the neutral Higgs bosons decaying to lepton pairs. The latest results of CMS [15] and ATLAS [16] with an integrated luminosity of around 1 fb^{-1} shave a large area of the high $\tan\beta$ region, as shown in the right plot in Fig. 2. The successful run of the LHC even allows us to access the low $\tan\beta$ region.

3. Conclusions

We have discussed the scenario of light neutralino dark matter in the MSSM, which is motivated by the direct detection experiments DAMA/LIBRA, CoGeNT, and CRESST. In our previous study, we showed that a narrow parameter region with high values of $\tan\beta$ was consistent with

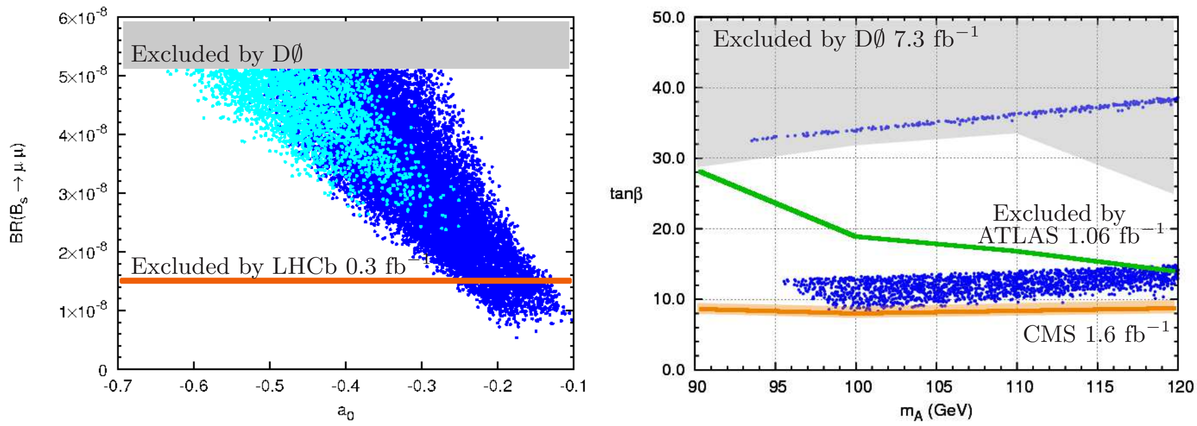

Figure 2. Left: Branching ratio of $B_s \to \mu^+\mu^-$ as a function of a_0 with the points on the high $\tan\beta$ strip. Light blue points satisfy the LEP bounds on Higgs boson masses, which are excluded by the latest LHCb result (orange line). Right: Allowed points overlayed with the constraints to the Higgs parameters m_A and $\tan\beta$ from the neutral Higgs boson search at hadron colliders. The latest results of both CMS and ATLAS (also D∅) exclude the high $\tan\beta$ strip at 95% CL.

the results of DAMA/LIBRA and CoGeNT, and it could satisfy the cosmological requirements and the particle physics constraints. In this talk, we have updated our numerical analysis with the latest LHC results. It turns out that the high $\tan\beta$ region comes into disfavour with the new bound to $B_s \to \mu^+\mu^-$ reported by LHCb. In addition, the neutral Higgs boson search at CMS and ATLAS brings a critical constraint to this scenario, which excludes a large part of the parameter region with small m_A and large $\tan\beta$. There is still discussion on the background estimation for the relevant process [17], and thus we should wait for the consensus. It is expected that the next official release from LHC will finally examine the viability of this scenario.

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